Research Article

Rotation as a strategy to increase the sustainability of potato crop[1]

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ABSTRACT

Potato cultivation is characterized by a high use of inputs, which results in soil degradation and contamination. Crop rotation is a good practice to counteract these problems. This study aimed to assess the sustainability of three rotation sequences (potato-pea-potato, potato-oat-pea and potato-potato-oat) using the sustainability assessment methodology oriented to agricultural experiments associated with soil management. It was observed that, both environmentally and economically, potato-potato-oat is the most sustainable treatment, while potato-oat-pea is the most socially sustainable. Balancing the three dimensions, potato-potato-oat is the most sustainable treatment, with sustainability index of 0.85, while potato-pea-potato is the least sustainable one, with 0.64. The potato-potato-oat rotation sequence generates a less negative environmental impact, as well as a higher social equity and economic return for the farmer.

KEYWORDS: *Solanum tuberosum*, *Pisum sativum*, *Avena sativa*.

RESUMO

Rotação como estratégia para
aumentar a sustentabilidade da cultura da batata

O cultivo da batata caracteriza-se por elevado uso de insumos, o que resulta na degradação e contaminação do solo. A rotação de culturas é uma boa prática para neutralizar tais problemas. Objetivou-se avaliar a sustentabilidade de três esquemas de rotação (batata-ervilha-batata, batata-aveia-ervilha e batata-batata-aveia), utilizando-se a metodologia de avaliação da sustentabilidade orientada a experimentações agrícolas associadas ao manejo do solo. Verificou-se que, ambiental e economicamente, batata-batata-aveia é o tratamento mais sustentável, enquanto batata-aveia-ervilha é o mais socialmente sustentável. Ao equilibrar as três dimensões, batata-batata-aveia é o tratamento mais sustentável, com índice de sustentabilidade de 0,85. No outro extremo está batata-ervilha-batata, com 0,64. A sequência de rotação batata-batata-aveia gera menor impacto ambiental negativo, bem como maior equidade social e retorno econômico para o produtor.

PALAVRAS-CHAVE: *Solanum tuberosum*, *Pisum sativum*, *Avena sativa*.

INTRODUCTION

Potato (*Solanum tuberosum*) is classified as the main non-cereal food in the world (Padmanabhan et al. 2016), with a production area of more than 17 million ha and yield of more than 374 million Mg in 2022 (FAO 2024).

As in most countries in the world, in Colombia, potato is one of the main crops, producing 160.505 ha (Agronet 2023). This is characterized by its production in high mountain areas and high use of agricultural supplies, mainly fertilizers, contributing to erosion and groundwater contamination problems (Rees et al. 2011, Machebe et al. 2023). Compared to other seasonal crops, the continuous potato cultivation can generate medium to high profitability for farmers. Nevertheless, due to intensive production, detrimental effects, such as excessive application of agrochemicals (Zegada-Lizarazu & Monti 2011, Valbuena et al. 2021), erosion (Kachanoski & Carter 1999, Quintero-Angel et al. 2022) and soil quality reduction (Nelson et al. 2009, Farfán et al. 2020), are generated.

To counteract the harmful effects caused by the mismanagement of potato crops, crop rotation is one of the most important, since it has been adapted and used by potato producers in the most important production regions (Liang et al. 2019, Liu et al. 2019). Crop rotation can have multiple beneficial effects on the environment, including optimizing energy use,

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maintaining surface water quality by reducing runoff and soil erosion, maintaining groundwater quality by reducing nutrient leaching and soil quality by conserving the dynamics of microbial communities (Larkin & Honeycutt 2006, Khakbazan et al. 2019, Liang et al. 2019). Generally, in crop rotation studies, in addition to evaluating the effect on yield, the dynamics of soil properties over time is also evaluated (He et al. 2012, Wszelaczynska et al. 2012, Shibabaw et al. 2018).

Despite the environmental benefits generated by crop rotation, farmers do not widely adopt this method, because lower incomes are obtained than those with monoculture (Liu et al. 2019). Nevertheless, in recent decades, potato rotation practices have spread among farmers in Colombia. The concept of not repeating more than two potato cycles in the same place has become widespread. To ensure optimal results with the rotation sequence, it is necessary to determine the crops that best balance both agroecological conditions and farmer requirements. Not all crops and combinations within the rotation sequence have the same results (Liu et al. 2019).

To determine which production strategy generates the least negative environmental impact while promoting high economic returns and social equity, it is necessary to evaluate new production strategies from the perspective of sustainability. In this sense, Monsalve et al. (2023) developed the sustainability assessment methodology oriented to soil-associated agricultural experiments (SMAES), an adaptable and quantifiable methodology for the evaluation of sustainability oriented toward soil-associated agricultural experiments (fertilization, tillage, irrigation and rotation). In SMAES, the outputs are interpreted through a sustainability index that assembles the environmental, social and economic information of the experiment (Monsalve et al. 2023).

Thus, this study aimed to determine which rotation sequence(s) with potato generate the highest crop sustainability in the Cundi-Boyacense high mountains Colombian region using SMAES.

MATERIAL AND METHODS

The experiment was carried out in 2014-2015, in the Agrosavia-Tibaitata Research Center in Mosquera, Colombia (4º41'18.84"N, 74º12'22.67"W and altitude of 2,560 m), where the average relative humidity is 80 % and the average temperature 14 ± 1 ºC.

Potato (*Solanum tuberosum* cv. Diacol Capiro), pea (*Pisum sativum* vr. Santa Clara) and forage oat (*Avena sativa* vr. Cayuse) seeds were used, and three rotation sequences were evaluated: potato-pea-potato, potato-oat-pea and potato-potato-oat. A randomized complete block design was established with 3 treatments and 12 experimental units (4 replicates per treatment). Each experimental unit had an area of 20 m^2. Potato was planted with 0.35 m between plants and 0.9 m between rows, pea in rows spaced 50 cm with 10 cm between plants, and oat broadcast planted throughout the experimental unit. The planting densities were 2.8, 7.5 and 200 plants m^{-2}, respectively for potato, pea and oat. The fertilization scheme was the same for all potato cycles, building the formula from the soil properties and the plant requirements using chemical synthesis fertilizers mixed with compost. Oat and pea were not fertilized.

The sustainability assessment of the three rotation sequences was conducted with the sustainability assessment methodology oriented to soil-associated agricultural experiments (SMAES), which requires the construction of one production system inventory for each experimental unit. Some of the environmental and social indicators and all economic indicators were estimated with the production system inventory (Monsalve et al. 2023), in which all agricultural exploitation and resource consumption data (inputs, labor and outputs) were collected (data not shown).

Figure 1 shows a scheme that summarizes the SMAES methodology divided into three macro-processes: 1) experiment development (tillage, fertilization, irrigation or rotation), during which soil, plant and climate variables were measured and the production system inventory constructed individually for each experimental unit or plot; 2) the entire dataset (variables or raw indicators) was divided according to the dimension (environmental, social or economic) and attributed to which it belonged. Subsequently, i) each indicator was parameterized by defining the thresholds (whether there was an optimum or this optimum was the highest or lowest value in the dataset); ii) a correlation, variance and comparison analysis was performed to define the base indicators; iii) which were normalized; iv) each base indicator underwent a checklist of selection criteria to define the

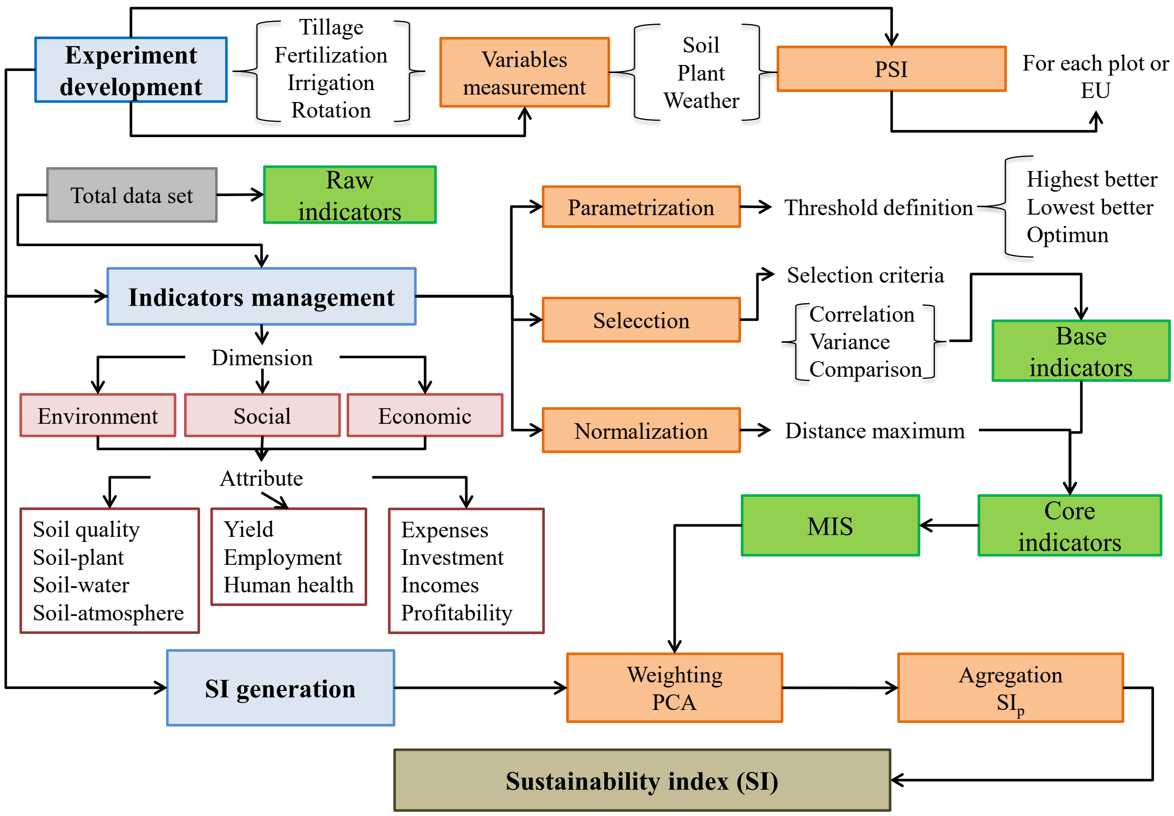

Figure 1. Synthesis of the sustainability assessment methodology oriented to soil-associated agricultural experiments (SMAES). The blue, green, orange, gray and brown boxes indicate macro-processes, achievements, activities, data organization and outcome (SI), respectively. PSI: production system inventory; EU: experimental unit; MIS: minimum indicators set; PCA: principal component analysis; SI_p: product of weighted indicators. Source: Monsalve et al. (2023).

core indicators and the minimum indicator set; 3) the sustainability index, where weights were assigned to each core indicator (weighting) by principal component analysis, was built. The indicators were added using the product of the weighted indicator technique to obtain the sustainability index value (Monsalve et al. 2023).

Table 1 shows all the raw indicators evaluated in the experiment. In total, 42 raw indicators were measured or estimated, being 31 environmental, 8 social and 11 economic.

Table 2 shows the characteristics of the core indicators (selected indicators) for the SMAES analysis. To define the core indicators, the indicator selection method included in SMAES (Monsalve & Henao 2022) was used (selection process not shown). In summary, this method divided the indicators according to their hierarchy (raw, baseline and core indicators). The minimum indicators set was defined according to the compliance of the types of criteria (mandatory, main, alternative non-mandatory and correlation) and the score obtained through a checklist. Indicators in the minimum indicators set represented each attribute and dimension in SMAES (Monsalve et al. 2023).

For all environmental indicators estimated by life cycle assessment, all resource consumption and emissions referred to a functional unit of mass of 1 kg of fresh commercial potato. Extraction of the raw material to the farm gate was the limit of the system, i.e., a life cycle assessment from cradle to door. It was considered a single subsystem: fertilization. The background processes included the production of fertilizers, whose production data came from the Ecoinvent V3.4 database (Ecoinvent Centre 2017).

The social indicators of each attribute were obtained from the production system inventory based on a business model, where all technical, administrative and management processes followed the Colombian legal framework (CCB 2019, DIAN 2019). All the variable costs (plant material, fertilizers, crop protection and wages, among others)

Table 1. Raw environmental, social and economic indicators.

Environmental	Environmental
Soil organic carbon (%)	Marine water toxicity (kg 1.4-DB eq)
Carbon stock (Mg ha^{-1})	Potential eutrophication (kg PO_4^{3-} eq)
pH (dimensionless)	Potential acidification (kg SO_2 eq)
Electrical conductivity (dS m^{-1})	Global warming potential (kg CO_2 eq)
Effective cationic exchange capacity ($cmol_c$ kg^{-1})	Ozone depletion (kg CFC-11 eq)
Phosphorus (mg kg^{-1})	**Social**
Exchangeable bases (K^+, Ca^{2+}, Mg^{2+}, Na^+) ($cmol_c$ kg^{-1})	Yield (kg)
Micronutrients (Fe, Cu, Mn, Zn, B) (mg kg^{-1})	Percentage of first category (%)
Bulk density (g cm^{-3})	Wages per cycle per hectare (unit)
Available water capacity (%)	Wages per year per hectare (unit)
Water retention curve (0.01, 0.03, 0.1, 0.3 and 1.5 MPa) (%)	Work effort indicator (%)
Water content (cm)	High and maximum work effort (%)
Texture (dimensionless)	Formation of photochemical oxidants (kg C_2H_4 eq)
Aggregate stability (%)	Human toxicity (kg 1.4-DB eq)
Weighted mean diameter of soil peds (mm)	**Economic**
Geometric mean diameter of soil peds (mm)	Variable costs ($ ha^{-1})
Nutrient concentration in plant tissue (mg kg^{-1})	Fixed costs ($ ha^{-1})
NO_3^- concentration of soil solution (mg L^{-1})	Investment ($ ha^{-1})
Soil management assessment framework (dimensionless)	Gross income ($ ha^{-1})
Soil quality indicator using principal component analysis (dimensionless)	Net income ($ ha^{-1})
Soil quality simple additive indicator (dimensionless)	Net present value ($)
Soil quality weighted additive indicator (dimensionless)	Benefit-cost ratio ($)
Land use (m^2 kg^{-1})	Opportunity rate obtained (%)
Amount of water per kilogram produced (L kg^{-1})	Internal rate of return (%)
Amount of nitrogen per kilogram produced (g kg^{-1})	Breakeven point by quantity (kg ha^{-1})
Fresh water toxicity (kg 1.4-DB eq)	Breakeven point by price ($ kg^{-1})

and fixed costs (leasing, public services, salaries and administration, among others) associated with production were accounted for and included in the analysis.

RESULTS AND DISCUSSION

As shown in Table 3, according to the mandatory selection criteria, all evaluated indicators were related to the sustainability objective and were quantifiable, specifically interpretable, and transparent and standardized. This suggests that the change in the indicators can be interpreted by the modification of the system when applying the treatments. At the same time, indicators were based on clearly defined, verifiable and scientifically acceptable data collected through standardized and affordable methods, so that they can be reliably replicated and compared with each other.

In the human health attribute of the social dimension, a score of 0 was obtained using the high and maximum work effort indicator for the redundancy criterion, since this indicator was part of the work effort indicator. This implies that these two indicators are directly and proportionally related. This is the same situation as gross income in the income attribute of the economic dimension (Table 3). In this case, gross income was part of the net income. The soil management assessment framework and soil quality indicator using principal component analysis showed no significant differences between treatments and obtained a score of 0 in this criterion (Table 3).

Regarding the correlation criterion, in the environmental dimension, very highly significant correlations were observed between all indicators of the soil-water and soil-atmosphere attributes. The same was evident for the soil-plant attribute indicators, except for the amount of nitrogen per kilogram produced, which did not show a significant correlation with the other indicators of this attribute.

For the human health attribute in the social dimension, the work effort indicator and high and maximum work effort showed the most highly significant correlations (Table 4). This was expected, as there is redundancy in these two indicators. The labor effort was constructed from the sum of all

Table 2. Core indicators of the minimum indicators set selected in the environmental, social and economic dimensions.

Indicator	Threshold*	Method
		Environmental dimension - Attribute
Soil quality		
SQ_{SA}	HVB	SQ_{SA} = $(SC_{Tt} - SC_{Min})/(SC_{Max} - SC_{Min})$, where SQ_{SA} is the soil quality simple additive indicator, SC_{Tt} the total score achieved by each experimental unit of each treatment, SC_{Min} the minimum possible score and SC_{Max} the maximum possible score
Soil-plant		
LU	LVB	LU = 1 m^2/kgP, where LU is the land use and kgP the harvested product mass in kg
Soil-water		
PE	LVB	$PE = \sum_i[(v_i/M_i \times No_2/A_e)/(1/M_{PO4}^{3-} \times No_2/A_p)]\ m_i$ where PE is the potential eutrophication, v_i the amount of N or P moles in a molecule of the compound i, M_i the molecular weight (kg mol^{-1}), No_2 the amount of O_2 moles consumed during algae depletion, A_e the amount of N or P moles contained in a molecule of algae and m_i the weight of the substance 1 (kg) (Guinée et al. 2004). Estimated by life cycle assessment
Soil-atmosphere		
GWP	LVB	$GWP = \sum_i i\{[\int_0^T a_i\ c_i\ (t)dt]/[\int_0^T a_{CO2}\ c_{CO2}\ (t)dt]\ m_i$ where GWP is the global warming potential, T the time (years), a_i the heating produced by the increase in the concentration of gas i (W m^{-2} kg^{-1}), c_i(t) the concentration of gas i in time (t) (kg m^{-3}) and m_i the mass of the substance i (kg). The corresponding CO_2 values are included in the denominator (Heijungs & Guinée 2012). Estimated by life cycle assessment
		Social dimension
Food security		
Yield	HVB	Potato: weighing all harvested tubers [20-24 weeks after planting (wap)] from 10 plants in the central area of each experimental unit Pea: weighing all pods of 20 plants from the central area of each experimental unit. Between two and three harvests were made at the end of pod filling (14-17 wap) Oat: weighing all plants cut from four 0.5 m^2 square templates, obtained from the central area of each experimental unit at the end of the vegetative period (9-10 wap)
Employment generation		
JY	LVB	JY: wages per year per hectare (day's pay $year^{-1}$ ha^{-1})
Human health		
HT	LVB	$HT = \sum_{i,n} HTP_{i,n} \times f_{i,n} \times m_i$ where HT is the human toxicity, $f_{i,n}$ the fraction of substance i transported from crop to environmental compartment n and m_i the mass emitted from each pollutant i (Antón 2004). Estimated by life cycle assessment
		Economic dimension
Expenses		
VC	LVB	VC: variable costs; sum of variable costs
Investment		
IV	LVB	IV: investment; all costs associated with the initial economic investment prior to field activities
Incomes		
NI	HVB	NI = GI - (VC + FC), where NI is the net income, GI the gross income, VC the variable cost and FC the fixed costs
Profitability		
B/C	HVB	B/C = GI/(VC + FC), where B/C is the benefit-cost ratio, GI the gross income, VC the variable cost and FC the fixed costs

* HVB: highest value is the best; LVB: lowest value is the best.

cultivation labors, including those with high and maximum labor effort (G4 and G5) (Monsalve et al. 2020).

Regarding the economic dimension, a highly significant correlation among the indicators of the three attributes was observed (Table 4). Some indicators were built from others where incomes and expenses were the basis, explaining the correlation.

According to the selection criteria shown in Table 3, the minimum indicators set was composed

Table 3. Indicator selection process.

Attribute	Indicator	Mandatory								Main non-mandatory							Alternate non-mandatory						Correlated		Total
		StOb	QuAt	SpIn	TrSt	NoRd	SgDf	W_{CS} 0.5		AfMs	PrTz	MsEd	ObSt	VrRt	W_{CS} 0.2		AcTn	PtDv	PrFu	AgGt	W_{CS} 0.2		W_{CS} 0.1		
Environmental dimension																									
Soil quality	SQ_{SMAF}	2	1	1	1	1	0	0.0		3	0	2	2	1	0.7	0.15	2	1	1	1	1.0	0.20	1.0	0.10	0.00
	SQ_{SA}	2	1	1	1	1	3	0.8	0.41	3	0	2	2	1	0.7	0.15	2	0	1	1	0.8	0.16	1.0	0.10	0.81
	SQ_{W}	2	1	1	1	1	5	1.0	0.50	3	0	2	2	1	0.7	0.15	2	0	1	1	0.8	0.16	1.0	0.10	0.91
	SQ_{PCA}	2	1	1	1	1	0	0.0		3	0	2	2	1	0.7	0.15	2	0	1	1	0.8	0.16	1.0	0.10	0.00
Soil-plant	LU	2	1	1	1	1	5	1.0	0.50	3	0	2	1	1	0.6	0.13	2	0	1	0	0.6	0.12	0.7	0.07	0.81
	W-kg	2	1	1	1	1	5	1.0	0.50	3	0	0	1	1	0.5	0.09	1	0	1	0	0.4	0.08			0.00
	N-kg	1	1	1	1	1	5	0.9	0.45	3	0	2	2	1	0.7	0.15	1	0	1	0	0.4	0.08	1.0	0.10	0.78
Soil-water	FWT	2	1	1	1	1	5	1.0	0.50	2	0	0	0	1	0.3	0.05	1	0	0	0	0.2	0.04			0.00
	MWT	2	1	1	1	1	5	1.0	0.50	2	0	0	0	1	0.3	0.05	1	0	0	0	0.2	0.04			0.00
	PE	2	1	1	1	1	5	1.0	0.50	2	0	0	1	1	0.4	0.07	2	0	0	0	0.4	0.08	1.0	0.10	0.75
Soil-atmosphere	PA	2	1	1	1	1	5	1.0	0.50	2	0	0	0	1	0.3	0.05	1	0	0	0	0.2	0.04			0.00
	GWP	2	1	1	1	1	5	1.0	0.50	2	0	0	0	1	0.3	0.05	2	0	0	0	0.4	0.08	1.0	0.10	0.73
	OLD	1	1	1	1	1	5	0.9	0.45	2	0	0	0	1	0.3	0.05	1	0	0	0	0.2	0.04			0.00
Social dimension																									
Food security	Yd	2	1	1	1	1	5	1.0	0.50	3	0	2	2	1	0.7	0.15	2	1	1	0	0.8	0.16	1.0	0.10	0.91
	FCat	2	1	1	1	1	3	0.8	0.41	3	0	2	2	1	0.7	0.15	1	0	0	0	0.2	0.04			0.00
Employment generation	JC	2	1	1	1	1	5	1.0	0.50	1	0	2	1	1	0.5	0.09	2	0	1	0	0.6	0.12	1.0	0.10	0.81
	JY	2	1	1	1	1	5	1.0	0.50	1	0	2	2	1	0.5	0.11	2	0	1	0	0.6	0.12	1.0	0.10	0.83
Human health	EL_{B}	2	1	1	1	1	5	1.0	0.50	3	0	0	0	1	0.4	0.07	0	0	0	0	0.0	0.00	1.0	0.10	0.67
	$EL_{B(4.5)}$	2	1	1	1	0	5	0.0		3	0	0	0	1	0.4	0.07	0	0	0	0	0.0	0.00	1.0	0.10	0.00
	PO	2	1	1	1	1	5	1.0	0.50	2	0	0	0	1	0.3	0.05	1	0	0	0	0.2	0.04			0.00
	HT	2	1	1	1	1	5	1.0	0.50	2	0	0	1	1	0.4	0.07	1	0	0	0	0.2	0.04	1.0	0.10	0.71
Economic dimension																									
Outcomes	VC	2	1	1	1	1	5	1.0	0.50	1	0	2	1	1	0.5	0.09	1	1	1	0	0.6	0.12	1.0	0.10	0.81
	FC	2	1	1	1	1	5	1.0	0.50	1	0	2	0	0	0.3	0.05	1	1	1	0	0.6	0.12			0.00
Investment	IV	2	1	1	1	1	5	1.0	0.50	1	0	2	0	0	0.3	0.05	1	1	1	0	0.6	0.12	1.0	0.10	0.77
Incomes	GI	2	1	1	1	0	5	0.0		3	0	2	1	1	0.6	0.13	1	0	1	0	0.4	0.08			0.00
	NI	2	1	1	1	1	3	0.8	0.41	3	0	2	2	1	0.7	0.15	2	1	1	0	0.8	0.16	1.0	0.10	0.81
Profitability	B/C	2	1	1	1	1	5	1.0	0.50	3	0	0	2	1	0.5	0.11	2	1	1	1	1.0	0.20	0.4	0.04	0.85
	NPV	2	1	1	1	1	5	1.0	0.50	1	0	0	2	1	0.4	0.07	2	0	1	1	0.8	0.16			0.00
	ORO	2	1	1	1	0	5	0.0		1	0	0	2	1	0.4	0.07	1	0	1	1	0.6	0.12	0.4	0.04	0.00
	IRR	2	1	1	1	1	5	1.0	0.50	1	0	0	2	1	0.4	0.07	2	0	1	1	0.8	0.16	0.4	0.04	0.77
	BPQ	2	1	1	1	1	5	1.0	0.50	1	0	0	2	1	0.4	0.07	1	0	1	1	0.6	0.12	1.0	0.10	0.79
	BPP	2	1	1	1	1	3	0.8	0.41	1	0	0	2	1	0.4	0.07	1	0	1	1	0.6	0.12	0.4	0.04	0.64

StOb: related to the sustainability objective; QuAt: quantifiable; SpIn: specifically interpretable; TrSt: transparent and standardized; NoRd: not redundant; SgDf: significantly different; Wcs: weight assigned to the selection category; AfMs: affordable measurement; PrTz: parameterized; MsEd: measured or estimated; ObSt: related to the study objective; VrRt: variable between repetitions; AcTn: acceptance; PtDv: participatory development; PrFu: present and future balance; AgGt: aggregate; SQ_{SMAF}: soil management assessment framework (dimensionless); SQ_{SA}: soil quality simple additive indicator (dimensionless); SQ_{W}: soil quality weighted additive indicator (dimensionless); SQ_{PCA}: soil quality indicator using principal component analysis (dimensionless); LU: land use (m^2 kg^{-1}); W-kg: amount of water per kilogram produced (L kg^{-1}); N-kg: amount of nitrogen per kilogram produced (g kg^{-1}); FWT: fresh water toxicity (kg 1.4-DB eq); MWT: marine water toxicity (kg 1.4-DB eq); PE: potential eutrophication (kg PO_4^{3-} eq); PA: potential acidification (kg SO_2 eq); GWP: global warming potential (kg CO_2 eq); OLD: ozone depletion (kg CFC-11 eq); Yd: yield (kg); FCat: first category percentage (%); JC: wages per cycle per hectare (unit); JY: wages per year per hectare (unit); EL_{B}: work effort indicator (%); $EL_{B(4.5)}$: high and maximum work effort (%); PO: formation of photochemical oxidants (kg C_2H_4 eq); HT: human toxicity (kg 1.4-DB eq); VC: variable costs ($ ha^{-1}); FC: fixed costs ($ ha^{-1}); IV: investment ($ ha^{-1}); GI: gross income ($ ha^{-1}); NI: net income ($ ha^{-1}); B/C: benefit-cost ratio ($); NPV: net present value ($); ORO: opportunity rate obtained (%); IRR: internal rate of return (%); BPQ: breakeven point by quantity (kg ha^{-1}); BPP: breakeven point by price ($ kg^{-1}). Highlighted cells correspond to core indicators.

of soil quality weighted additive indicator (soil quality attribute), land use (soil-plant), potential eutrophication (soil-water) and global warming potential (soil-atmosphere) in the environmental dimension, with scores of 0.91, 0.81, 0.75 and 0.73, respectively. In the social dimension, it was composed of yield (food security), wages per year per hectare (employment generation) and human toxicity (human health), with scores of 0.91, 0.83 and 0.71, respectively. In the economic dimension, it was composed of variable costs (outcomes), investment, net income (incomes) and benefit-cost ratio (profitability), with scores of 0.81, 0.77, 0.81 and 0.85, respectively.

Table 4. Algorithm to calculate the correlation selection criterion.

Attribute	Indicator	Correlation matrix[§]													Selection Factor				∑CS
															FS_1	FS_2	FS_3	FS_N	
Environmental dimension																			
		SQ_{SMAF}	SQ_{SA}	SQ_W	SQ_{PCA}	LU	W-kg	N-kg	FWT	MWT	PE	PA	GWP	OLD					
Soil quality	SQ_{SMAF}		0.37	0.53	0.64										0.5	4.0	4.0	1.0	
	SQ_{SA}	0.37		0.63	0.66										0.4	4.0	4.0	1.0	0.71
	SQ_W	0.53	0.63		0.69										0.4	4.0	4.0	1.0	0.81
	SQ_{PCA}	0.64	0.66	0.69											0.3	4.0	4.0	1.0	
Soil-plant	LU						0.78	0.16							0.5	2.0	2.0	0.7	0.75
	W-kg					0.78		0.49							0.4	2.0	2.0	0.7	0.67
	N-kg					0.16	0.49								0.7	3.0	3.0	1.0	0.68
Soil-water	FWT									1.00	1.00				0.0	1.0	1.0	1.0 †	0.59
	MWT								1.00		1.00				0.0	1.0	1.0	1.0 †	0.59
	PE								1.00	1.00					0.0	1.0	1.0	1.0 †	0.65
Soil-atmosphere	PA												1.00	1.00	0.0	1.0	1.0	1.0 †	0.59
	GWP											1.00		1.00	0.0	1.0	1.0	1.0 †	0.63
	OLD											1.00	1.00		0.0	1.0	1.0	1.0 †	0.55
Social dimension																			
		Yd	FCat	JC	JY	EL_B	$EL_{B(4.5)}$	PO	HT										
Food security	Yd		0.34												0.7	2.0	2.0	1.0 †	0.81
	FCat	0.34													0.7	2.0	2.0	1.0 †	0.59
Employment generation	JC				1.00										0.0	1.0	1.0	1.0 †	0.71
	JY			1.00											0.0	1.0	1.0	1.0 †	0.73
Human health	EL_B						0.99	0.21	0.21						0.5	3.0	3.0	1.0	0.57
	$EL_{B(4.5)}$					0.99		0.07	0.07						0.6	3.0	3.0	1.0	
	PO					0.21	0.07		1.00						0.6	3.0	3.0	1.0 †	0.59
	HT					0.21	0.07	1.00							0.6	3.0	3.0	1.0 †	0.61
Economic dimension																			
		VC	FC	IV	GI	NI	B/C	NPV	ORO	IRR	BPQ	BPP							
Outcomes	VC		0.51												0.5	2.0	2.0	1.0 †	0.71
	FC	0.51													0.5	2.0	2.0	1.0 †	0.67
Investment	IV														-	-	-	1.0	0.67
Incomes	GI					0.98									0.0	1.0	1.0	1.0 †	
	NI				0.98										0.0	1.0	1.0	1.0 †	0.71
Profitability	B/C							0.98	1.00	0.97	0.05	0.71			0.3	2.0	2.0	0.4	0.81
	NPV						0.98		0.98	0.92	0.13	0.57			0.3	3.0	3.0	0.6	0.73
	ORO						1.00	0.98		0.96	0.04	0.71			0.3	2.0	2.0	0.4	
	IRR						0.97	0.92	0.96		0.27	0.84			0.2	2.0	2.0	0.4	0.73
	BPQ						0.05	0.13	0.04	0.27		0.73			0.8	5.0	5.0	1.0	0.69
	BPP						0.71	0.57	0.71	0.84	0.73				0.3	2.0	2.0	0.4	0.60

SQ_{SMAF}: soil management assessment framework (dimensionless); SQ_{SA}: soil quality simple additive indicator (dimensionless); SQ_W: soil quality weighted additive indicator (dimensionless); SQ_{PCA}: soil quality indicator using principal component analysis (dimensionless); LU: land use (m^2 kg^{-1}); W-kg: amount of water per kilogram produced (L kg^{-1}); N-kg: amount of nitrogen per kilogram produced (g kg^{-1}); FWT: fresh water toxicity (kg 1.4-DB eq); MWT: marine water toxicity (kg 1.4-DB eq); PE: potential eutrophication (kg PO_4^{3-} eq); PA: potential acidification (kg SO_2 eq); GWP: global warming potential (kg CO_2 eq); OLD: ozone depletion (kg CFC-11 eq); Yd: yield (kg); FCat: first category percentage (%); JC: wages per cycle per hectare (unit); JY: wages per year per hectare (unit); EL_B: work effort indicator (%); $EL_{B(4.5)}$: high and maximum work effort (%); PO: formation of photochemical oxidants (kg C_2H_4 eq); HT: human toxicity (kg 1.4-DB eq); VC: variable costs ($ ha^{-1}); FC: fixed costs ($ ha^{-1}); IV: investment ($ ha^{-1}); GI: gross income ($ ha^{-1}); NI: net income ($ ha^{-1}); B/C: benefit-cost ratio ($); NPV: net present value ($); ORO: opportunity rate obtained (%); IRR: internal rate of return (%); BPQ: breakeven point by quantity (kg ha^{-1}); BPP: breakeven point by price ($ kg^{-1}). †: correlated indicators in each attribute.

No treatment highlighted all the dimensions and attributes of each dimension. Regarding the environmental dimension, potato-potato-oat showed the best results for the soil quality attributes (together with potato-oat-pea) and soil-plant relationship, represented by the soil quality simple additive and land use indicators, respectively. Potato-potato-oat generated a higher yield (food security attribute), what suggests a better use of land and water (Table 5).

Regarding the social dimension, potato-potato-oat achieved the highest yield, while potato-oat-pea obtained the best results for employment generation and human health attributes, using the lowest wages per year and generating the least labor effort (Table 5).

The potato-potato-oat treatment achieved the best global results for the economic dimension, by requiring a lower investment and obtaining the highest net income (incomes) and the highest benefit-cost ratio (profitability) (Table 5). These results were related to the high yield obtained by this treatment. Potato-pea-potato required the highest investment and the highest fixed and variable costs, despite its lower yield. This generated poor economic, social and environmental results (Table 4). In this last aspect, the yield obtained by potato-pea-potato did not compensate for the higher use of fertilizers. Life cycle assessment is carried out based on the amount of inputs used to produce 1 kg of the harvested product (Heijungs & Guinée 2012). The goal is to produce more with less resources.

Based on the assignment of weights carried out through the principal component analysis, weights were equally assigned to all attributes of each dimension (Table 6), indicating that all attributes had a similar influence on the sustainability of the system.

Environmentally and economically, potato-potato-oat was the most sustainable treatment (Figure 2), agreeing with the results shown by its attributes and indicators (Table 5). Socially, potato-oat-pea was the most sustainable treatment, while the lowest results were obtained in potato-pea-potato

Table 5. Results of the evaluation for each dimension, attribute and indicator for each treatment.

Attribute	Indicator	Potato-pea-potato	Potato-oat-pea	Potato-potato-oat
		Environmental dimension		
Soil quality	SQ_{SMAF}	0.87 a	0.86 a	0.89 a
	SQ_{SA}	0.37 b	0.53 a	0.48 a
	SQ_{W}	0.61 b	0.62 ab	0.64 a
	SQ_{PCA}	0.46 a	0.48 a	0.48 a
Soil-plant	LU	0.653 b	0.704 c	0.273 a
	W-kg	306.48 c	206.07 b	122.14 a
	N-kg	7.56 c	4.65 a	6.27 b
Soil-water	FWT	0.033 c	0.020 a	0.028 b
	MWT	128.82 c	79.19 a	106.78 b
	EP	3.4E-04 c	2.1E-04 a	2.9E-04 b
Soil-atmosphere	AP	2.0E-03 c	1.2E-03 a	1.6E-03 b
	GWP	7.0E-01 c	4.3E-01 a	5.8E-01 b
	OLD	4.4E-08 c	2.7E-08 a	3.7E-08 b
		Social dimension		
Food security	Yd	69,607 c	84,288 b	119,535 a
	FCat	0.746 b	0.863 a	0.726 b
Employment generation	JC	79 c	51 a	63 b
	JY	237 c	154 a	189 b
Human health	EL_{B}	3.4740 b	3.4267 a	3.7316 c
	$EL_{B(4,5)}$	0.5440 b	0.5407 a	0.8195 c
	PO	5.92E-05 c	3.64E-05 a	4.91E-05 b
	HT	0.24 c	0.15 a	0.20 b
		Economic dimension		
Outcomes	VC	15.7 c	11.1 a	14.0 b
	FC	20.1 c	19.3 b	18.8 a
Investment	IV	14.42 c	12.24 b	9.53 a
Incomes	GI	56.23 a	41.82 c	54.48 b
	NI	20.42 a	11.40 b	21.65 a
Profitability	B/C	1.53 b	1.31 c	1.63 a
	NPV	35.26 b	18.83 c	38.21 a
	ORO	0.33 b	0.22 c	0.39 a
	IRR	3.83 b	2.66 c	5.12 a
	BPQ	40,895 a	73,290 b	84,318 c
	BPP	1021.86 b	980.75 b	393.64 a

Equal letters indicate no significant differences among treatments (Tukey; $p < 0.05$; n = 15). Highlighted cells correspond to core indicators.

Table 6. Results of the indicator weighting process by principal component analysis.

Parameters	Environmental (PCj)			Social (PCj)			Economic (PCj)		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
Eigen values	1.732	2.3E-05	3.5E-07	1.400	1.020	0.036	1.525	1.293	0.026
Variability (%)	1.000	0.000	0.000	0.653	0.347	0.000	0.582	0.418	0.000
Accumulated (%)	1.000	1.000	1.000	0.653	1.000	1.000	0.582	1.000	1.000
PCj (%)	100			65	35		58	42	

Dimension	Attribute	Eigen vectors (E_{PCj}):			(Eigen vectors)^2: λj		PC1 x λ1	PC2 x λ2	W_k
		E_{PC1}	E_{PC2}	E_{PC3}	λ1	λ2			
Environmental	Soil quality	0.552	-0.254	0.794	0.304	0.065	0.222	0.018	0.24
	Soil-plant	0.065	0.963	0.263	0.004	0.926	0.003	0.252	0.26
	Soil-water	-0.588	-0.066	0.387	0.346	0.004	0.252	0.001	0.25
	Soil-atmosphere	-0.588	-0.066	0.387	0.346	0.004	0.252	0.001	0.25
Social	Food security	0.714	-0.042	0.699	0.509	0.002	0.333	0.001	0.33
	Employment generation	-0.234	0.927	0.294	0.055	0.859	0.036	0.298	0.33
	Human health	0.660	0.373	-0.651	0.436	0.139	0.285	0.048	0.33
Economic	Outcomes	-0.453	0.558	-0.594	0.206	0.312	0.120	0.130	0.25
	Investment	-0.542	0.434	0.680	0.294	0.188	0.171	0.079	0.25
	Incomes	0.454	0.558	-0.222	0.206	0.312	0.120	0.130	0.25
	Profitability	0.543	0.434	0.369	0.294	0.188	0.171	0.079	0.25

for social sustainability and in potato-oat-pea for economic sustainability (Figure 2).

Balancing the three sustainability dimensions, potato-potato-oat was the most sustainable treatment, with sustainability index of 0.85, although it did not achieve the highest score in the social dimension (Figure 2).

The potato-potato-oat rotation achieved the highest sustainability index, generating the best results in the environmental and economic dimensions, and ranked second in the social dimension. This suggests that the potato-potato-oat sequence was the most sustainable for the study conditions, coinciding in part with the experiment of

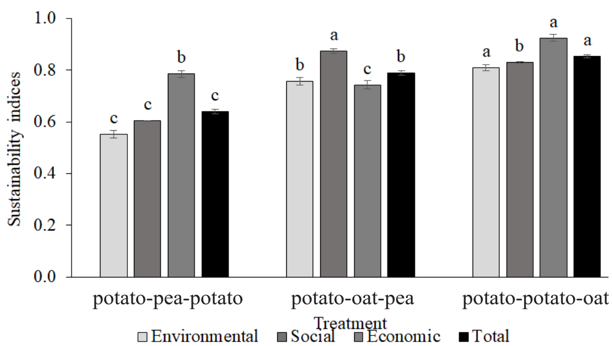

Figure 2. Comparison of sustainability indices among treatments. "Total" represents the cumulate of the three sustainability dimensions. Equal letters indicate no significant differences among treatments (Tukey; $p < 0.05$; $n = 15$).

Tadesse et al. (2021), who described a better benefit at the end of the rotation cycles when the predecessor crop was potato ending with another Poaceae, such as malting barley, obtaining statistically higher biomass yields when compared to all other rotations. By implementing two potato cycles within the rotation, the yield increased over just one potato cycle, which directly and positively influenced the social and economic dimensions. From the point of view of the producer (crop owners), this rotation would be favorable, as it was economically more profitable. However, it should be considered that, in this case, forage oat is used for animal feed, mainly cattle. This crop is produced mainly by farmers who alternate agricultural activity with livestock. Despite occupying the second place in the social dimension, the food security component of the potato-potato-oat rotation presented statistical differences with respect to the other rotations, highlighting that, during two cycles, it maintained a food livelihood for a small farmer, confirming the statements of Wilches (2019), who said that the potato crop in Colombia is key to food security for millions of people who base their diet and depend economically on this tuber. Additionally, the last rotation in fodder oat presents additional sustenance for the farmer due to the livestock associated with the crop and the production of milk on the farm.

Oat is a crop that requires less crop activity. This crop does not require additional labor than planting, fertilization and harvesting, as it does not require pruning or weed control after planting. This explains why rotations with oat (potato-oat-pea and potato-potato-oat) required the least wages, thus obtaining the best results for wages per year per hectare. SMAES assumes that the fewer wages required, the higher the social sustainability, assuming, in this case, the point of view of the producer (Monsalve et al. 2023). At the same time, the potato-potato-oat rotation requires fewer inputs, since the oat crop was not fertilized. Farmers assume that the amount of nutrients left in reserve after fertilization to the potato crop is enough to produce one cycle of oat.

The potato-oat-pea rotation is frequently used by farmers and can increase the availability of nutrients, such as phosphorus, boron and zinc, without altering the physical soil properties (Vargas et al. 2022). In addition, it stands out in the social attribute due to the lower salaries per year (less work effort), being an alternative to potato monoculture.

Despite ranking second in water management and global warming potential, the potato-potato-oat rotation also generates a better land use and is associated with a higher level of soil fertility. According to the soil quality simple additive indicator, the soil where the experiment was carried out had a medium fertility level (0.53). In studies with low fertility soils, changes in the soil characteristics due to rotation schemes are notable (see Sharifi et al. 2014, Shibabaw et al. 2018). However, Muthoni & Kabira (2010), He et al. (2012) and Nyiraneza et al. (2015) mentioned that changes in soil properties due to crop rotation were evident in the long term. In the preset study, three crop cycles (approximately two years) were evaluated, suggesting that the selected soil quality indicator was sensitive to soil disturbance in the medium term.

Sustainability assessments by framing the environment, society and economy made possible to globally evaluate agricultural production systems, but defining which crop sequence improves the environmental, economic and social aspects of the crop system is a difficult process. However, SMAES offers a way to estimate which potato rotations are sustainable with less subjectivity.

CONCLUSION

The potato-potato-oat rotation generated the highest sustainability according to the sustainability assessment methodology oriented to soil-associated agricultural experiments (SMAES). This rotation sequence generated the lowest environmental impact, the highest economic return for the producer, and obtained the second place in social equity.

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